

# Neutrino Processes with Hot Nuclei in Supernovae\*

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In this paper, we calculate cross sections for charged-current neutrino-nucleus processes occurring under presupernova conditions. To treat thermal effects we extend self-consistent Skyrme-QRPA calculations to finite temperature by using the formalism of thermo field dynamics. The numerical results are presented for the sample nuclei,  $^{56}\text{Fe}$  and  $^{82}\text{Ge}$ .

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## 1. Introduction

Neutrino reactions play a central role during the collapse and shock revival phase of core-collapse supernova [1]. The reliable calculations of neutrino-nucleus cross sections requires a detailed knowledge of the Gamow-Teller (GT) strength in nuclei. The problem is rather complicated, since the finite-temperature supernova environment implicitly demands to consider GT transitions between thermally excited nuclear states. Such transitions remove the reaction threshold and dominate the low-energy cross sections.

In [2], the neutrino-nucleus cross sections were computed using the large-scale shell model (LSSM) diagonalization approach. Although the LSSM approach provides a detailed GT strength distribution for the nuclear ground and lowest excited states, it partially employs the Brink hypothesis when treating GT transitions from high-lying excited states. In addition, present computer capabilities allow LSSM calculations only for iron-group nuclei ( $A \leq 65$ ), whereas neutrino reactions with heavier mass and neutron-rich nuclei also may play important role in core-collapse supernovae. Here, we present the alternative method to account for thermal effects on neutrino-nucleus reactions.

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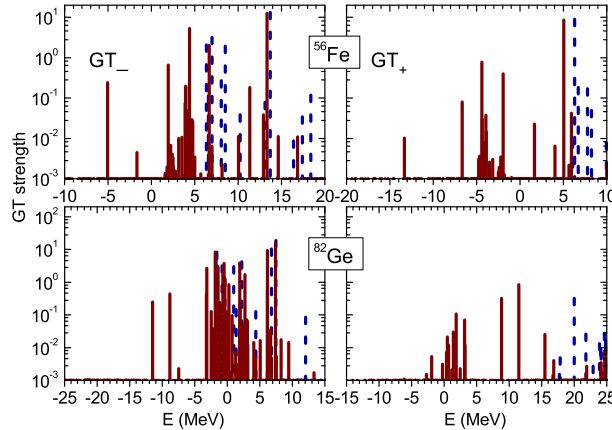


Fig. 1. The  $GT_-$  (left panels) and  $GT_+$  (right panels) strength functions for  $^{56}\text{Fe}$  and  $^{82}\text{Ge}$  calculated at  $T = 0$  (dashed peaks) and  $T = 1.72$  MeV (solid peaks).

## 2. Formalism

In [3], thermal effects on the cross sections of neutrino-nucleus reactions were studied by QRPA calculations extended to finite temperature by the thermo field dynamics formalism (TQRPA)[4, 5]. The technique does not rely on the Brink hypothesis and allows to calculate the thermal strength function in a thermodynamically consistent way, i.e., without violating the principle of detailed balance. In [3], the TQRPA calculations were based on a nuclear Hamiltonian with locally adjusted parameters. In Ref. [6], a self-consistent approach combining the TQRPA with the Skyrme energy density functional has been introduced and applied to neutral-current neutrino-nucleus reactions. In the present note we use the Skyrme-TQRPA to predict the cross sections for  $(\nu_e, e^-)$  and  $(\bar{\nu}_e, e^+)$  reactions with  $^{56}\text{Fe}$  and  $^{82}\text{Ge}$ .

## 3. Results

In Fig. 1, we display on a logarithmic scale the  $GT_-$  and  $GT_+$  distributions in  $^{56}\text{Fe}$  and  $^{82}\text{Ge}$  nuclei calculated with the SLy4 forces for  $T = 0$  (i.e. for the ground state) and  $T = 1.72$  MeV ( $2 \times 10^{10}$  K). The parametrization SLy4 rather well reproduces the experimental positions of the  $GT_-$  and  $GT_+$  resonances in  $^{56}\text{Fe}$ . Because the Brink hypothesis is not fulfilled within the TQRPA, the GT strength functions change with temperature. Thermal effects are most significant for the  $GT_+$  distribution in  $^{82}\text{Ge}$ , where the temperature rise lowers the resonance peak by about 8 MeV. As shown in [3], the physical origin of this significant downward shift is the interplay between two unblocking mechanisms of  $GT_+$  transitions in neutron-rich

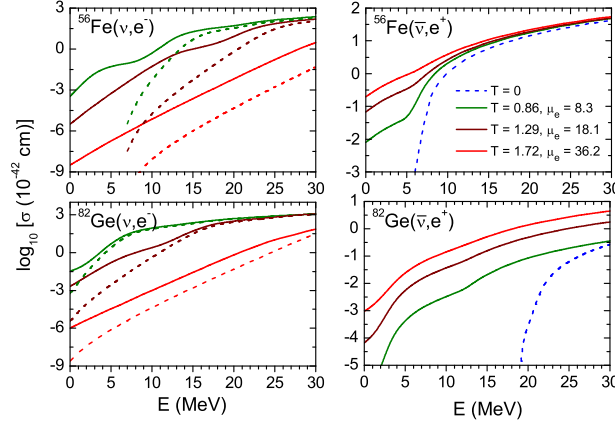


Fig. 2. Cross sections of absorption reactions of  $\nu_e$  and  $\bar{\nu}_e$  by  $^{56}\text{Fe}$  and  $^{82}\text{Ge}$ . The cross sections are computed at finite temperature and finite chemical potential (both in MeV). For comparison the ground state results are shown by the dashed lines.

nuclei: configuration mixing induced by pairing correlations and thermal excitations. Thermal excitations also unblock low- and negative-energy GT transitions. The strength of negative-energy transitions exponentially increases with temperature in accordance with the principle of detailed balance [3]. Nevertheless, the TQRPA preserves the Ikeda sum rule.

Figure 2 shows the cross sections obtained with the GT thermal strength functions computed using TQRPA with the SLy4 force. In the collapsing core, the chemical potential of the degenerate electron gas increases faster than the temperature. Therefore, neutrino absorption cross sections are drastically reduced for low-energy neutrinos due to electron blocking in the final states. In contrast, antineutrino absorption cross sections are strongly enhanced at finite temperature. For  $^{56}\text{Fe}$ , this enhancement is mostly caused by negative-energy  $\text{GT}_+$  transitions from thermally excited states. Such transitions dominate the cross section for  $E_{\bar{\nu}} < 5$  MeV. In  $^{82}\text{Ge}$ , negative-energy transitions are suppressed and the observed cross section enhancement reflects the downward shift of the  $\text{GT}_+$  resonance and the thermal unblocking of low-energy transitions.

In Fig. 3, we compare the finite temperature cross sections for  $^{56}\text{Fe}$  obtained with the SLy4, SGII and SkM\* Skyrme parametrizations. As seen from the plots, the spread in the cross sections computed with different Skyrme forces is less than an order of magnitude. We also note the Skyrme-TQRPA results are noticeable larger than the LSSM ones and the discrepancy reduces with increasing neutrino energy. As shown in [3], the reason

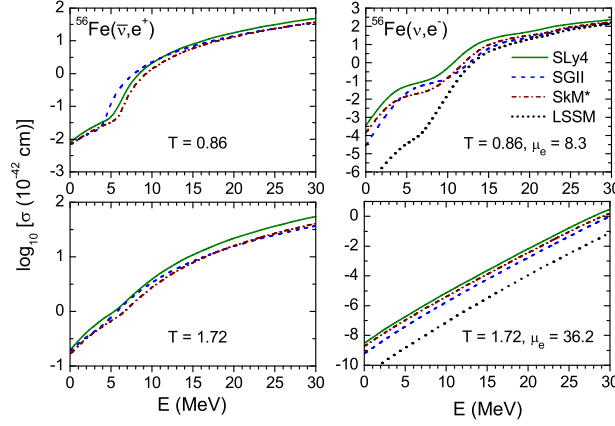


Fig. 3. Finite temperature cross sections for  $^{56}\text{Fe}(\nu_e, e^-)$   $^{56}\text{Fe}(\bar{\nu}_e, e^+)$  reactions computed with different Skyrme forces. For  $\nu_e$  absorption the LSSM results are also shown [2]. The temperature and chemical potential are in MeV.

for this discrepancy is that shell-model calculations are partially based on the Brink hypothesis when treating GT transitions from excited states and therefore underestimate the contribution of low- and negative-energy thermally unblocked transitions.

#### 4. Summary

Cross sections for (anti)neutrino absorption by hot nuclei in the supernova environment were calculated for  $^{56}\text{Fe}$  and  $^{82}\text{Ge}$  within the Skyrme-TQRPA approach. Temperature-driven changes in the cross sections were explained by considering thermal effects on the  $\text{GT}_{\pm}$  strength distributions. It was found that different Skyrme forces predict cross sections which do not differ significantly. This could indicate a robustness of the results against the variation of the Skyrme force parameters.

#### REFERENCES

- [1] H.-T. Janka, *et al.*, Phys. Rep. **442**, 38 (2007).
- [2] J. Sampaio, *et al.*, Phys. Lett. B **511**, 11 (2001), *ibid.* **529**, 19 (2002).
- [3] A. A. Dzhirov, *et al.*, Phys. Rev. C **89**, 035805 (2014), *ibid.* **92**, 045804 (2015).
- [4] Y. Takahashi and H. Umezawa, Int. J. Mod. Phys. B **10**, 1755 (1996).
- [5] A. A. Dzhirov and A. I. Vdovin, Int. J. Mod. Phys. E **18**, 1535 (2009).
- [6] A. A. Dzhirov, *et al.*, Phys. Rev. C **94**, 015805 (2016).